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# PEE POWER® urinal II – Urinal scale-up with microbial fuel cell scale-down for improved lighting

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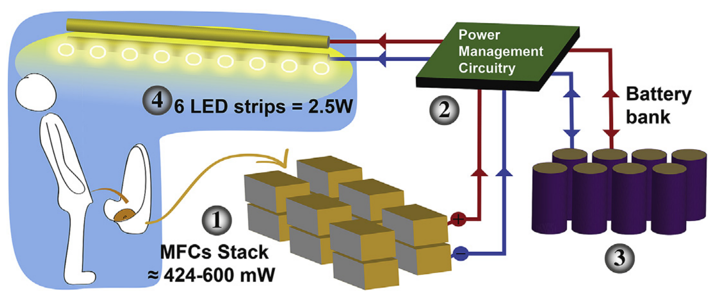
## HIGHLIGHTS

- First field trial of a novel design of scalable membraneless MFCs.
- The MFC stack did not require any energy input to function.
- 30% more power from 1/3 of the total volumetric footprint compared to 2015.
- 92% higher COD removal from half the retention time compared to 2015.
- 88% Chemical Oxygen Demand removal at 44 h HRT.

## GRAPHICAL ABSTRACT

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## ABSTRACT

A novel design of microbial fuel cells (MFC) fuelled with undiluted urine was demonstrated to be an efficient power source for decentralised areas, but had only been tested under controlled laboratory conditions. Hence, a field-trial was carried out to assess its feasibility for practical implementation: a bespoke stack of 12 MFC modules was implemented as a self-sufficient lit urinal system at UK's largest music festival. Laboratory investigation showed that with a hydraulic retention time (HRT) of 44 h, a cascade of 4 modules (19.2 L displacement volume) was continuously producing ≈150 mW. At the same HRT, the chemical oxygen demand (COD) was reduced from 5586 mg COD·$L^{-1}$ to 625 mg COD·$L^{-1}$. Field results of the system under uncontrolled usage indicate an optimal retention time for power production between 2h30 and ≈9 h. When measured (HRT of ≈11h40), the COD decreased by 48% and the total nitrogen content by 13%. Compared to the previous PEE POWER® field-trial (2015), the present system achieved a 37% higher COD removal with half the HRT. The 2016 set-up produced ≈30% more energy in a third of the total volumetric footprint (max 600 mW). This performance corresponds to ≈7-fold technological improvement.

## 1. Introduction

Microbial fuel cells (MFCs) are energy transducers, first reported in 1911 [1], which produce electricity through the bio-electro-oxidation of organic compounds. Over the last two decades, during which research in the field has intensified, oxygen has become the most common end-terminal electron acceptor in the cathode, due to its availability and high redox value [2–5]. Individual MFCs produce relatively low levels of power, hence a plurality of units must be assembled in stacks to reach useful power levels [6,7]. However, deploying MFC stacks in real environments presents two main challenges: cost and complexity. Self-stratifying membraneless MFCs (SSM-MFC) have been shown to

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address such a dual need [8]. At the same time, SSM-MFCs have demonstrated the capacity to be scaled-up in size, up to a certain extent, without significant power density losses [8]. The principle behind SSM-MFCs is to employ the ability of microorganisms to vertically self-stratify across physicochemical conditions of any given water column (e.g. lake, or urine). In such a column, cathodes are placed on the top whilst the anodes are placed on the bottom layers. This configuration is somewhat similar to single compartment MFCs with multiple cathodes and anodes. The main difference being that the cathode is partially submerged into the electrolyte and occupies about half of the available urine column's depth. Since the upper layer of the urine column (i.e. the catholyte) is separated from the bottom layer (i.e. the anolyte) by a bioelectrochemical gradient, an interpretation could be that this gradient is a transient membrane renewed after each feeding pulse. This aspect led to the naming of this type of MFC a SSM-MFC: Self-stratifying membraneless MFCs. However, until now this type of MFC has only been tested under controlled laboratory conditions [8,9].

This study was carried out from an implementation perspective and focused on the generation of energy from urine. Employing urine as fuel presented several advantages, one of which is that MFCs can be fuelled directly with neat urine (i.e. without any dilution nor pre-treatment) [10], a waste stream representing 75% of the nitrogen found in domestic wastewater [11]. Such a technology could lower the burden on wastewater treatment plant. By integrating the MFC technology in waterless urinals, the energy consumption of wastewater treatment plants would be reduced, but with useful energy being produced near the source (e.g. for charging smart phones, providing light or automation of sanitary peripherals) [9,12,13].

Although numerous reports focus on improving the technology, there is a relatively small number of field trial studies describing pilot-scale MFC systems deployed under real conditions. The first practical demonstration, which can be considered as field-trial, is to be found in the world of electronic/robotic with the "gastrobot" [14], or the Ecobot series [6,15]. Along these prototypes demonstrating the potential of MFC to act as power source, another series of early successful trials demonstrated the use of benthic and marine MFCs to power sensors [16–18]. As discussed in these previous studies, the implementation of MFC implies the use of power management circuitry (e.g. DC-DC converters, power harvester, capacitors/batteries) to match the MFC's lower but constant energy production to the application's higher, and sometimes intermittent, energy needs. Aside robotics and marine environments, wastewater treatment is the other main niche in which research focuses. A recent review documents the performance of litre-scale MFCs treating real wastewater at continuous flow mode, thus illustrates the potential for implementation and technology readiness [19]. Up until 2010, only three pilot-scale trials had been tested [20]. The first large pilot-scale MFC stack treating wastewater was fuelled by brewery waste in Yatala (Queensland, Australia), where twelve 3 m high MFC modules with a total volume of 1 $m^3$ were used [20]. Since then, several studies have been conducted "out-of-the-lab" and/or at a pilot-scale: MEC for hydrogen production from wastewater [21], benthic microbial fuel cells [18], MFC in constructed wetland for wastewater treatment [22,23] and prototypes to be integrated in wastewater treatment plants [19,24–31], Floating MFCs combined with plants that act as autonomous sensors able to transmit a signal in natural water bodies [32], and MFC-based urinal system [13], have also been reported.

The aim of the present trial was to assess the feasibility of SSM-MFC to be deployed as an electricity-generating sanitation solution in decentralised areas for periodic usage [9]. In order to test SSM-MFC in real conditions, the site for the trial should (i) have a need for lighting, automation or device charging, (ii) have a high number of users to provide the fuel and (iii) have a need for waterless *in-situ* treatment. Due to the existing collaboration between the Bristol BioEnergy Centre and the Glastonbury Music Festival, the PEE POWER® urinal was tested in real conditions for a short period of time (3 weeks in total, including the 6 days of the music festival) at Glastonbury 2016. The Glastonbury Music Festival attracts approximately 250,000 people (festival goers and staff) and has a strong environmental agenda, with a high interest for on-site treatment and off-grid power. However, for such a purpose the system had to be re-designed to meet the on-site needs (i.e. a very high number of users per day; automatic feeding) [13]. Practically this meant scaling-up the whole system, whilst keeping the MFC modules smaller than the ones used in the PEE POWER® urinal of 2015, adapting a passive feeding mechanism, and setting-up the appropriate energy management system, to harvest the energy and power the higher-energy consuming lights. Compared to its predecessor [13], the aim was to provide twice the amount of lighting (the urinal was twice the size) with a smaller footprint MFC system ($<1/3$ vol by comparison). Overall, the present study provides (i) results from laboratory investigation, (ii) performance under real conditions-of-use at the festival (iii) a self-sufficient system comprising MFCs and peripherals delivering a service to the users.

## 2. Materials and methods

Prior the trial, larger MFC modules were initially tested under laboratory conditions and then the system was assembled and tested on site, at the Glastonbury Music Festival 2016.

### 2.1. MFC modules construction and cascades configurations

#### 2.1.1. Scaling-up the module size

The SSM-MFC modules employed had a similar design as the ones previously described [8,9]. The cathodes were in the aerobic upper layers of the urine column whilst the anodes were in the anaerobic lower layer of the column. Due to the amount of fuel to be treated being greater (up to 1000 L $d^{-1}$), the size of individual modules was increased by a factor of 2 in length and width and the modules had the following external dimensions: 400 mm length, 300 mm width and 170 mm height ("large module"). A total of 38 MFCs were inserted within this volume and all were electrically connected in parallel. The total footprint volume of a module was 20.4L, of which 11.2L was occupied by the MFCs (i.e. internal volume). The rest of the volume was occupied by air since the upper 5 cm of each box served as a support for upstream modules, resulting in a displacement volume of 4.8L of electrolyte. The modules were inoculated with the output waste-stream from other urine-fuelled MFCs. The first module tested had a feeding regime of 1.25L neat urine pulses every 2 h. Urine (pH between 8.5 and 9.2) was collected and pooled daily, from anonymous individuals with no known previous medical conditions.

#### 2.1.2. Laboratory cascade configuration

Two cascades of 4 modules each were assembled and initially tested in the laboratory. A cascade is defined as a set of modules where the output of one is feeding into the input of the next one. Hence a cascade is a series of modules treating the same fuel. Both cascades were fed from the same gravity-feed mechanism which was pulsing 3.4L every 2 h through two outputs, one for each cascade. As such, each cascade was receiving 1.7L every 2 h, unless otherwise stated. As the pulse-feed regime and the power produced are directly related [8], when the feeding rate was increased, so was the load. With this same hydraulic configuration, three electrical connections were tested: (i) both cascades were electrically independent and all four modules within each cascade connected in parallel, (ii) all four modules within each cascade were connected in parallel, and the two cascades connected in series, and (iii) the modules were connected in parallel by pairs, and the four pairs were then connected in series. The applied loads were consequently adapted to the electrical configurations.

#### 2.1.3. Glastonbury 2016 system configuration

To compare the performance with the 2015 trial that used larger